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Arm/hand cooling in the Cold Exposure Survival Model

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Defence R&D Canada
Technical Report
DCIEM TR 2001-157
November 2001

National Defence Défense nationale

Canada

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Abstract

The previously developed Cold Exposure Survival Model (CESM) is limited to predictions of cognitive impairment and survival time (time to lethal hypothermia) under conditions of cold exposure. The present development addresses motor function impairment of the arms and hands that usually occurs before cognitive impairment and well before the onset of lethal hypothermia. Two data sources were used for this purpose, one based on a field study designed to simulate survival situations and the other based on a review of the literature. The field study involved 28 healthy males on survival training divided into five groups and exposed for 6 continuous days on different occasions during two winter seasons. Despite mean (± SD) air temperatures ranging from –24.4 ± 3.9 to 4.4 ± 2.5°C among the groups, deep body temperature (T_{core}) remained normal averaging from 37.1 to 37.5°C. However, finger temperature (T_{finger}) was significantly correlated to T_{air} as follows: $T_{finger} = 16.7 + 0.28 \cdot T_{air}$ ($r = 0.53$; $p < 0.0001$). Grip strength, knot-tying, and nut-bolt assembly performance decreased most for the coldest-exposed group, which is consistent with the low T_{finger} measured for this group (9.4 ± 3.4°C). Percentages of their maximum performance in these respective tasks were 87.5 ± 9.0, 69.2 ± 12.1, and 83.8 ± 18.1%. The following significant regressions were obtained using all the subjects' data: grip strength (%) = $94.7 + 0.30 \cdot T_{air}$ ($r = 0.48$; $p < 0.0001$); knot-tying (%) = $93.0 + 0.53 \cdot T_{air}$ ($r = 0.39$; $p < 0.0001$); and nut bolt (%) = $84.1 + 1.33 \cdot T_{finger}$ ($r = 0.33$; $p < 0.0002$). No decrement in cognitive performance as evaluated with tests of logical reasoning, planning, and vigilance was found in any of the groups, and is attributed to the subjects' maintenance of a normal T_{core}. These data were consistent with other studies conducted under controlled laboratory conditions and were used in a revision of CESM. The revised model predicts the times to moderate and severe losses of hand and arm function based on skin temperatures of 15 and 4°C for the finger, and muscle temperatures of 21 and 10°C for the arm, respectively. Additional predictions are the times to a reference performance level based on 50% of the maximal effort of an average mid-age male under normal body temperature. In this case, the predicted performances are instantaneous maximal force (as determined by grip strength) and sustained high intensity work effort (as determined by repetitive push-ups). These additional predictions should provide a more complete assessment of a casualty's survival status in the revised CESM.

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Résumé

Le modèle de survie à l'exposition au froid (MSEF) antérieur ne portait que sur les troubles cognitifs et le temps de survie (temps précédant l'hypothermie létale) lors d'une exposition au froid. Les travaux présents portent sur les troubles de motricité des bras et des mains, qui surviennent habituellement avant les troubles cognitifs et bien avant l'hypothermie létale. Deux sources de données ont été utilisées pour ces travaux, l'une étant une étude effectuée en conditions réelles simulant des situations de survie et l'autre étant une analyse documentaire. L'étude portait sur 28 sujets en instruction de survie, de sexe masculin et en bonne santé, répartis en cinq groupes exposés au froid durant six jours consécutifs, à différentes occasions, au cours de deux hivers. Malgré des moyennes de température ambiante (± l'écart-type) variant de -24,4 ± 3,9 °C à 4,4 ± 2,5 °C, la température interne du corps ($T_{centrale}$) des sujets est demeurée normale, entre 37,1 °C et 37,5 °C (en moyenne). Cependant, la température des doigts (T_{doigts}) était étroitement liée à T_{air} selon la relation suivante : $T_{doigts} = 16,7 + 0,28 \cdot T_{air}$ ($r = 0,53$; $p < 0,0001$). La force de préhension et l'habileté à faire des nœuds et à monter des écrous et des boulons étaient à leur plus bas niveau dans le groupe soumis aux températures les plus froides, ce qui est en accord avec la faible T_{doigts} mesurée dans ce groupe (9,4 ± 3,4 °C). Les pourcentages du rendement maximal des sujets de ce groupe à chacune des épreuves susmentionnées étaient respectivement de 87,5 ± 9,0 %; 69,2 ± 12,1 % et 83,8 ± 18,1 %. Les régressions significatives suivantes ont été obtenues à partir des données provenant de tous les groupes : force de préhension (%) $= 94,7 + 0,30 \cdot T_{air}$ ($r = 0,48$; $p < 0,0001$); faire des nœuds (%) $= 93,0 + 0,53 \cdot T_{air}$ ($r = 0,39$; $p < 0,0001$); et monter des écrous et des boulons (%) $= 84,1 + 1,33 \cdot T_{doigts}$ ($r = 0,33$; $p < 0,0002$). Aucune diminution du rendement cognitif, mesurée à l'aide de tests de logique, de planification et de vigilance, n'a été observée pour les différents groupes, en raison du fait que la $T_{centrale}$ est demeurée normale tout au long des évaluations. Ces données sont en accord avec d'autres études qui ont été réalisées dans des conditions de laboratoire contrôlées, et elles ont servi à améliorer le MSEF. Le modèle perfectionné permet maintenant d'estimer le temps précédant une perte modérée et sévère de motricité des mains et des bras en se fondant sur une température de la peau des doigts de 15 °C (modérée) et de 4 °C (sévère), et une température des muscles du bras de 21 °C (modérée) et de 10 °C (sévère). Un autre calcul que permet maintenant le modèle est celui du temps précédant un rendement de référence, déterminé à 50 % de l'effort maximal d'un homme moyen, d'âge moyen, à une température corporelle normale. Dans ce cas, les prévisions du modèle portent sur la force maximale instantanée (mesurée par la force de préhension) et l'effort soutenu de travail intensif (mesuré par des redressements brachiaux [« push-ups »] continus). Ces prévisions supplémentaires, résultant des modifications apportées au MSEF, devraient permettre de mieux évaluer l'état des victimes d'une exposition au froid.

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Executive summary

The present Cold Exposure Survival Model (CESM) provides predictions of the limits of cognitive function and survival time (time to lethal hypothermia) under conditions of cold exposure. Impairment of the motor function of the arms and hands is also an important consideration, but is presently not predicted by CESM. This additional information should provide a more complete assessment of the casualty's survival status, and was the focus of the present revision of CESM.

Data required for the model revision were obtained from a review of the literature and from a field study specifically designed to simulate survival situations. The field study involved 28 healthy CF male members on survival training divided into five groups and exposed for 6 continuous days on different occasions during two winter seasons. Air temperatures ranged from –24.4 to 4.4°C among the groups. While deep body temperature did not change from normal, finger temperature (ranging from 9.4 to 18.0°C for the coldest to warmest-exposed groups) was significantly correlated to air temperature and impacted on the subjects' manual performance. For example, grip strength, knot tying, and nut-bolt assembly performance decreased by 13, 31, and 16%, respectively, for the coldest-exposed group. In general, dexterity performance decrements were noted for a finger temperature of less than 15°C. Not surprisingly, cognitive performance as evaluated with tests of logical reasoning, planning, and vigilance was not impaired in any of the groups due to the maintenance of a normal deep body temperature.

The manual arm-hand performance decrements under the field conditions reported herein are attributed to local tissue/muscle cooling and concur with previously published results under controlled laboratory conditions. The revised model predicts the times to moderate and severe losses of hand and arm function based on skin temperatures of 15 and 4°C for the finger, and muscle temperatures of 21 and 10°C for the arm, respectively. A moderate level of hand function loss is associated with some loss of dexterity/tactility resulting in cruder task assembly and longer performance time. Severe deterioration is associated with a near total inability to perform fine motor tasks. Moderate and severe levels of arm function loss are associated with muscle performances at 50% of maximum and at near zero, respectively.

Additional predictions are the times to a reference performance level based on 50% of the maximal effort of an average mid-age male under normal body temperature. This provides a relative measure of the casualty's ability, as opposed to the absolute degradations in performance described above. The predicted performances are based on an instantaneous maximal force (as determined by grip strength) and a sustained high intensity work effort (as determined by repetitive push-ups).

Accordingly, the revised CESM (v2.2) provides predictions of the times to absolute levels of moderate and severe losses of hand and arm function as the primary output while the relative predictions appear as the secondary output. In addition, CESM2 predicts the times to two limits of cognitive function where moderate and severe losses pertain to deep body temperatures of 34 and 32°C, respectively. Survival time (to lethal hypothermia) is still based on the attainment of a deep body temperature of 28°C. The additional predictions provide a more complete description of a casualty's condition during cold exposure and should further assist search and rescue decision-making.

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Sommaire

Le Modèle de survie à l'exposition au froid (MSEF) actuel permet de déterminer les limites des fonctions cognitives et le temps de survie (temps précédant l'hypothermie létale) lors d'une exposition au froid. Les troubles de motricité des bras et des mains sont également importants, mais le MSEF actuel n'est pas conçu pour en tenir compte. Ces données supplémentaires devraient donc permettre une meilleure évaluation de l'état des victimes d'une exposition au froid, et constituent le principal objet de la présente révision du MSEF.

Les données requises à la révision du modèle ont été obtenues par une analyse documentaire et par une étude effectuée en conditions réelles simulant spécifiquement des situations de survie. L'étude portait sur 28 membres masculins des FC en instruction de survie, en bonne santé et répartis en cinq groupes exposés au froid durant six jours consécutifs, à différentes occasions, au cours de deux hivers. Bien que, dans le courant de l'étude, la température ambiante ait varié de -24,4 °C à 4,4 °C, la température centrale des sujets est restée normale. Cependant, la température des doigts des sujets (variant de 9,4 °C pour le groupe exposé aux températures les plus faibles à 18,0 °C pour le groupe exposé aux températures les plus élevées) était étroitement liée à la température ambiante et a influencé leur dextérité. Par exemple, la force de préhension et l'habileté à faire des nœuds et à monter des écrous et des boulons ont diminué respectivement de 13 %, 31 % et 16 % dans le cas du groupe exposé aux températures les plus faibles. En général, on a noté une diminution de la dextérité des sujets à une température des doigts inférieure à 15 °C. Comme prévu, le rendement cognitif, mesuré à l'aide de tests de logique, de planification et de vigilance, n'a diminué dans aucun des groupes, en raison du maintien d'une température corporelle normale.

Les diminutions de rendement pour les épreuves de dextérité observées dans les conditions susmentionnées sont attribuables au refroidissement des tissus/muscles des bras et des mains et sont en accord avec les résultats publiés précédemment, obtenus dans des conditions de laboratoire contrôlées. Le modèle révisé permet maintenant de prévoir le temps précédant une perte modérée et sévère de motricité des bras et des mains en se fondant sur une température de la peau des doigts de 15 °C (modérée) et de 4 °C (sévère) et une température des muscles du bras de 21 °C (modérée) et de 10 °C (sévère). Une perte modérée de motricité des mains signifie une perte de dextérité/sensibilité compliquant l'exécution des tâches et en allongeant le temps d'exécution, et correspond à un rendement musculaire équivalant à 50 % de l'effort maximal. Une perte sévère de motricité signifie une quasi-incapacité d'effectuer les tâches et correspond à un rendement musculaire presque nul.

Un autre calcul que permet maintenant le modèle est l'estimation du temps précédant un taux de rendement de référence, déterminé à 50 % de l'effort maximal d'un homme moyen, d'âge moyen, à une température corporelle normale. Ce calcul permet d'évaluer de façon relative les capacités des victimes plutôt que d'évaluer les diminutions de rendement absolues décrites précédemment. Les rendements prévus sont fondés sur la force maximale instantanée (mesurée par la force de préhension) et l'effort soutenu de travail intensif (mesuré par des redressements brachiaux [« push-ups »] continus).

En conséquence, le MSEF révisé (v2.2) permet, en premier lieu, la prévision des temps précédant les niveaux absolus de perte de motricité modérée et sévère des mains et des bras et, en second lieu, des prévisions relatives. De plus, le MSEF2 permet de prévoir les temps

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précédant des pertes modérée et sévère des fonctions cognitives associées à une température centrale de 34 °C (modérée) et de 32 °C (sévère). Le calcul du temps de survie (précédant l'hypothermie létale), lui, est toujours fondé sur une température centrale de 28 °C. Ces prévisions supplémentaires permettent d'avoir une meilleure idée de l'état des victimes d'une exposition au froid et devraient aider à la prise de décisions lors d'opérations de recherche et de sauvetage de ces personnes.

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Acknowledgements

DCIEM gratefully acknowledges several agencies for their support that made this work possible. This study was funded by the Department of National Defence New Search and Rescue Initiatives Program (NIFID No. 99003, Project No. DND 15-99) with the assistance of Capt. D. Kirkland. Logistical and resource support for the field study were generously provided by the CF School of Survival and Aeromedical Training through Maj. K. Glass and Capt. C. Hayes. Management of the field study and analyses of the field data were expertly conducted by C. Marrao and Prof. G.G. Giesbrecht of the Department of Physical Education and Recreation Studies of the University of Manitoba. We also thank all the subjects who selflessly volunteered for the field study under challenging conditions.

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Introduction

Survival situations place considerable demands on both the casualty and rescuer. Although advances in Search and Rescue (SAR) technologies allow for a rapid response, the casualty's ability to perform well both mentally and physically might determine their survival outcome. The present Cold Exposure Survival Model (CESM) provides predictions of functional time (FT; limit of self-help) and survival time (ST; time to lethal hypothermia) based on the physiological response to body cooling and on the physical processes of heat loss (Tikuisis 1995, 1997). However, the FT prediction is limited to cognitive/mental performance based on when the casualty reaches a deep body temperature of 34°C. Impairment of the motor function of the arms and hands usually occurs sooner but is presently not predicted by the model. This additional information would provide a more complete assessment of the casualty's survival status.

Harsh environmental conditions can also impose a debilitating thermal stress on the rescurers. Any improvement in the prediction of how cold impairs performance should be useful for SAR contingency planning, the prevention of injury, and the optimization of equipment and procedures. It is also important to recognize that the model's application goes beyond its primary role as a SAR decision aid; it has and continues to be useful for training instruction and for the evaluation of clothing protection.

Several studies [Dusek (1957), Gaydos (1958), Provins and Clarke (1960), Fox (1967), Enander (1989), Oksa et al. (1995), Heus et al. (1995)] have demonstrated various effects of cold exposure on performance, although most are short-term (< 3 h) and do not involve significant deep body cooling. This is because the initial exposure to cold causes vasoconstriction which lowers peripheral blood flow, thus preserving the thermal state of the deep body at the expense of limb cooling. Not only will sudden and/or acute cold stress affect the limbs more than the deep body in the short term, it can cause performance decrements due to the disturbing psychological impact imposed by the stress. If the cold stress persists, thermal strain of the whole body will increasingly develop over time leading to concomitant decrements in performance.

Two previous studies that have involved long term cold exposures to air are particularly relevant in the present context. Angus et al. (1979) reported on the general deterioration of vigilance and reaction time in 6 males living under arctic conditions for 16 days. Teichner and Kobrick (1955) reported on the marked decrement of visual-motor performance in 5 lightly clothed males continuously exposed for 12 days to 13°C air. Sleep deprivation was a contributor to the performance decrements reported in these studies. Unfortunately, these observations have limited value due to the lack of body temperature measurements, and thus the degree of body cooling associated with the performance decrements is unknown.

Giesbrecht et al. (1993) reported on the decrements in mental and motor performance during cold water immersion lasting up to 80 min. Deep body temperatures as low as 33°C were attained. The data amply demonstrate the psychological disturbance of the cold stress and the debilitating impact of muscle cooling in the limbs. In fact, latter studies (Oksa et al. 1995, Giesbrecht et al. 1995a) confirmed that arm performance decrements are almost entirely due to local muscle cooling and not necessarily directly dependent on deep body cooling.

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However, with sufficient deep body cooling, cognitive impairment would undermine any physical performance irrespective of local muscle temperature.

The present CESM limit of cognitive function based on a deep body temperature of 34°C can be considered conservative as it pertains more to complex mental tasks than to simpler ones (Giesbrecht et al. 1995b). The time limit of survival is also conservative as it is based on a deep body temperature of 28°C when rigidity normally sets in, vital signs become absent, and the threshold for ventricular fibrillation is reduced (Danzl et al. 1995, Giesbrecht 2001). These limits are retained in the revised CESM and additional limits will be assigned for arm-hand function based on both local and deep body cooling.

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Field study

An extensive field study was completed to obtain additional data for the revision of CESM. This study was conducted by Marrao (2001) as a M.Sc. thesis project. Twenty-eight healthy male military members volunteered to conduct a battery of mental and motor performance tasks daily during six days of survival training [Survival Evasion Resistance and Escape (SERE) course; CF School of Survival and Aeromedical Training]. These subjects were nearly evenly divided among five course periods where the average air temperature over the six days ranged among the groups from –24.4 to 4.4°C. Hereafter these groups will be referred as G1 through G5.

The various tasks involved two of strength (hand grip and shoulder-arm push), two of hand dexterity (knot-tying and nut-bolt assembly), two of cognitive function (logical reasoning and planning), and vigilance testing. In addition, the subjects were queried on their ratings of cold sensation (RCS) and perceived exertion (RPE) prior to conducting the tasks. Tasks were completed once a day during the evening except for the final session that took place on the morning of the last day. The shoulder-arm push performance results were ambiguous and no significant changes were found with cognitive function and vigilance. The latter is attributed to core (deep body) temperatures that largely remained normothermic, and also to the observation that the stress of the cold exposure was not a serious debilitating factor, at least within the range of air temperature (T_{air}) recorded during the trials. Table 1 provides the mean values of T_{air} and other variables of interest for all SERE groups.

Air temperature in the field was different ($P < 0.05$) among all the courses. Core temperature (T_{core}) was surprisingly high during all courses, although night-time lows of about 35.6°C were attained. Such values, however, are not considered hypothermic (Giesbrecht 2001). Finger temperature (T_{finger}) and T_{core} reported in Table 1 refer to the values measured during testing. Interestingly, G3 had a lower T_{core} than G1 and G5 despite being exposed to the highest average air temperature. Although speculative, it is possible that a higher rate of sweat production during work under the warmer condition lead to greater overall cooling due to enhanced heat loss through damp clothing.

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Table 1. Mean ± SD of selected variables measured daily during six days of field survival training. All reported temperatures were measured during testing. RCS and RPE are based on a 12-point scale where 0 refers to a normal unstressed state and 10 refers to a state of numbness and helplessness, respectively. Performance tasks are all scored as a percentage of baseline. Significant differences are stated in the text.

VARIABLE	SERE COURSE GROUP				
	G1 (N = 6)	G2 (N = 6)	G3 (N = 6)	G4 (N = 4)	G5 (N = 6)
T_{air} (°C)	-5.5 ± 1.8	-9.5 ± 5.1	4.4 ± 2.5	-24.4 ± 3.9	-11.9 ± 6.9
T_{core} (°C)	37.5 ± 0.3	37.4 ± 0.5	37.1 ± 0.3	37.3 ± 0.4	37.5 ± 0.5
T_{finger} (°C)	15.7 ± 3.7	13.9 ± 3.7	18.0 ± 4.2	9.4 ± 3.4	15.3 ± 5.6
RCS	1.6 ± 1.0	2.4 ± 0.9	1.6 ± 1.0	2.5 ± 1.2	1.9 ± 1.9
RPE	4.3 ± 2.4	3.7 ± 2.3	3.0 ± 1.9	3.6 ± 1.8	2.9 ± 1.7
Grip strength	91.9 ± 5.9	93.9 ± 10.4	98.4 ± 5.7	87.5 ± 9.0	88.9 ± 9.7
Knot-tying	105.2 ± 19.7	87.2 ± 16.7	93.9 ± 14.4	69.2 ± 12.1	87.8 ± 18.0
Nut bolt	112.0 ± 25.1	106.2 ± 11.5	104.6 ± 14.9	83.8 ± 18.1	99.1 ± 11.8

G4 had the lowest finger temperatures compared to the other groups, which were not different despite a tendency for T_{finger} to decrease with T_{air}. In fact, the two variables were significantly correlated: $T_{finger} = 16.7 + 0.28 \cdot T_{air}$ ($r = 0.53$; $p < 0.0001$). This relationship can be used to predict T_{finger} when only T_{air} is known.

Not surprisingly, G4 reported the highest cold sensation as they experienced the lowest T_{air}, and RCS did not differ among the other groups. In fact, RCS plateaued at about 2 for all groups during the entire field period. RCSs of 1 and 2 correspond to comfortable and slightly cool, respectively, consistent with the measured T_{core}. G1 reported a higher RPE than G3 and G5, otherwise there were no other differences. RPEs of 3 and 4 correspond to moderately and somewhat tired, respectively. RPE was not affected by environmental conditions, but by the time spent on course. That is, beginning with the second day of testing, the following relationship emerges: $RPE = 4.7 \cdot (1 - e^{-\ln 2\, ND/2})$ where ND is the number of days spent in the field ($r = 0.90$; SE is 0.7 for both parameter estimates of 4.7 and 2.0).

Hand grip strength of G4 was the lowest amongst the groups. A trend of decreasing grip strength with decreasing air temperature is evident in Table 1, and borne out by the following regression: Grip strength (%) $= 94.7 + 0.30 \cdot T_{air}$ ($r = 0.48$; $p < 0.0001$). Similarly, G4 had the lowest knot-tying performance of all groups and despite the anomalous improvement shown by G1 (Table 1), knot tying is also correlated to air temperature: Knot-tying (%) $= 93.0 + 0.53 \cdot T_{air}$ ($r = 0.39$; $p < 0.0001$). And finally, G4 also exhibited the lowest nut bolt assembly performance; however, in this case a significant regression was only obtained with finger temperature: Nut bolt (%) $= 84.1 + 1.33 \cdot T_{finger}$ ($r = 0.33$; $p < 0.0002$). A significant correlation

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with air temperature was not found in this case probably because of the trend of decreasing performance with increasing T_{air} for G1 through G3.

The greatest decrements in arm-hand performance occurred with G4 who were exposed to the coldest air temperatures (average of –24.4 ± 3.9°C). Grip strength decreased from 1.6 to 12.5% among the groups even though deep body temperatures remained near normal (average of about 37.3°C). Local arm cooling due to the low air temperature could have impacted on grip strength, at least according to the significant correlation between grip strength and T_{air} that was found. Average reductions to 69 and 84% of baseline performance of the coldest-exposed group (G4) in knot tying and nut bolt assembly, respectively, occurred with an average finger temperature of 9.4°C. Decrements recorded for the other groups were less but noticeable with finger temperature ≤ 15°C. The arm-hand performance decrements under field conditions thus reported concur with those previously published under laboratory conditions. No cognitive performance decrements were found suggesting that the cold stress *per se* was not a debilitating factor. Nor were any cognitive decrements expected in the absence of any central cold strain (deep body cooling). The data involving arm-hand performance due to local tissue cooling and other data from the literature will be used to revise CESM.

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Selection criteria of manual performance decrements

Manual performance decrements predicted for hand and arm functions will be based on separate criteria involving dexterity and strength, respectively. Dusek (1957) reviewed the loss of hand dexterity as a function of hand surface temperature from several different investigations. The various tasks conducted by individuals exposed to the cold included complex printing, gear assembly, knot tying, peg test, and a nut and bolt assembly. Dusek concluded that serious deterioration in hand function occurs when finger temperature drops below 16°C, and that below 4°C individuals begin to lose completely their ability to discriminate tactually and to perform fine motor skills. Mackworth (1953) conducted a finger tactile sensitivity test on individuals exposed to cold air resulting in skin temperatures as low as 7°C. He concluded that tactile deterioration began at finger temperatures between 20 and 25°C and plateaued at temperatures below 15°C. Clark (1961) concluded that 15.6°C was the limiting skin temperature for unaffected performance (knot-tying in this case). Lockhart et al. (1975) measured the manual dexterity of 32 subjects with finger temperatures of 18.3, 12.8, and 8.9° after slow and rapid cooling. The six tasks conducted by the subjects varied in degree of fine motor control, yet no decrement in performance was found at the highest finger skin temperature in all but two tasks where the decrement was less than 10%. Significant decrements occurred at the two lower skin temperatures, in concurrence with previous studies.

The above thresholds are consistent with the field trial results of Marrao (2001) and with Heus et al. (1995) who have suggested that 15°C is the minimum hand skin temperature necessary for safety and performance. Thus, in consideration of all of the above findings, the revised CESM will declare moderate and severe deterioration of hand dexterity when the finger skin temperature reaches 15 and 4°C, respectively (see Primary Output, Table 2). Severe loss of dexterity will also be declared if the body's core temperature reaches 32°C when cognitive function becomes severely impaired (Danzl et al. 1995) thus eliminating the possibility of any effective work. A moderate level of loss is associated with some loss of dexterity/tactility resulting in cruder task assembly and longer performance time. Severe deterioration is associated with a near total inability to perform fine motor tasks corresponding to the tasks described above.

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Table 2. CESM primary and secondary outputs.	
PRIMARY OUTPUT	
PREDICTION IN HOURS	
Survival Time	(based on T_{core} = 28°C)
Moderate Loss of Cognitive Function	(based on T_{core} = 34°C)
Severe Loss of Cognitive Function	(based on T_{core} = 32°C)
Moderate Loss of Hand Dexterity	(based on T_{finger} = 15°C)
Severe Loss of Hand Dexterity	(based on T_{finger} = 4°C or T_{core} = 32°C)
Moderate Loss of Arm Performance	(based on T_{muscle} = 21°C)
Severe Loss of Arm Performance	(based on T_{muscle} = 10°C or T_{core} = 32°C)

SECONDARY OUTPUT		
Strength of Individual	**PREDICTED TIMES (IN HRS) TO 50% OF MAXIMAL PERFORMANCE OF AN AVERAGE MALE BETWEEN 30 - 39 YRS OLD AT NORMAL BODY TEMPERATURE**	
	Grip Strength	***Push-Ups***
strong	(see Table 3 for target T_{muscle})	(see Table 4 for target T_{muscle})
average	(see Table 3 for target T_{muscle})	(see Table 4 for target T_{muscle})
weak	(see Table 3 for target T_{muscle})	< 0.1

Muscle temperature is deemed the primary determinate of gross arm motor function. Muscle temperature also governs nerve conduction velocity and the rate of tissue metabolism as quantified by the Q_{10} relationship. Q_{10} expresses the change in these functions for each 10°C change in tissue temperature (Bennett 1984), as follows:

$$\text{Perform} = \text{Perform}_{100\%} \cdot Q_{10}^{(T_{tis} - T_{ref})/10} \quad (1)$$

where T_{tis} and T_{ref} are the tissue and reference temperatures, respectively. The reference muscle temperature is assigned a thermoneutral value of 36°C. According to the results of several investigators (Paintal 1965, De Jong et al. 1966, De Jesus et al. 1973), the Q_{10} factor of nerve conduction velocity is approximately 1.6. In the present application, this value is adopted for predicting moderate and severe losses of general arm performance (as seen below,

a Q_{10} of 1.6 also lies between values applicable to instantaneous and sustained forces). A reduction in muscle performance of 50% of maximum is assumed to represent a moderate level of loss corresponding to a tissue temperature of 21°C (Primary Output, Table 2). Severe loss of performance will be arbitrarily declared if either the muscle temperature reaches 10°C (explained later on) or the body's core temperature reaches 32°C.

A moderate loss of performance, however, is relative to each individual. That is, weak and strong individuals will still exhibit different levels of absolute performance capacity for the same relative (eg., 50%) loss in performance. To provide more meaningful comparisons of performance deterioration especially when specific tasks are absolute force-dependent, the prediction of an individual's performance will also be arbitrarily compared to that of the 50th percentile healthy male between 30 and 39 years of age at normal body temperature. Grip strength and push-ups are two specific arm performance tests relevant to survival situations. The former test involves a maximal instantaneous force while the latter involves sustained heavy work.

The application of an instantaneous maximal force has a weak temperature dependency (low Q_{10}) in contrast to continuous work output, which has a higher Q_{10} dependency. According to various investigations involving human limb function (Clarke et al. 1958, Binkhorst et al. 1977, Ferretti et al. 1992), the Q_{10} factor for maximum instantaneous force is approximately 1.4, and this value is selected for the model prediction involving grip strength.

Continuous work output is a measure of dynamic performance that depends on several factors in addition to the duration of the work conducted. Of interest in the present application is the appropriate Q_{10} that encompasses work output and fatigue for sustained short-term high intensity work. From various investigations involving dynamic work of human limbs relevant to the present application (Edwards et al. 1972, Bergh and Ekblom 1979, Blomstrand et al. 1984), a Q_{10} factor of 1.8 is selected for the model prediction of the deterioration of the capacity to conduct high intensity arm work such as push-ups.

Thus, application of the Q_{10} function will lead to predictions of reductions in maximal instantaneous force and continuous high work capacities by factors of 1.4 and 1.8, respectively, for each 10°C decrease in muscle temperature. However, extrapolation at tissue temperatures below 20°C leads to disparately high performance values since no nerve signal processing, and therefore complete loss of function, occurs at nerve temperatures below 10°C (Paintal 1965, De Jong et al. 1966, Basbaum 1973). Further, it appears that Q_{10} itself is temperature-dependent as higher Q_{10} factors are evident with decreasing muscle temperature (Bennett 1984). Thus, while the Q_{10} factor can provide a reasonable approximation of the reduction in muscle performance for temperatures above 20°C, another description is required for temperatures between 10 and 20°C. Herein we propose the following first-order decay function for this purpose under the constraint that this function must be smooth and continuous with Q_{10} at the transition temperature of 20°C:

$$\text{Perform} = \text{Perform}_{100\%} \cdot A \cdot \left\{1 - e^{-k\,(T_{ti} - 10)}\right\} \qquad (2)$$

where A and k are fitting parameters. By equating Eqs. 1 and 2, and their derivatives at T_{ti} = 20°C, the respective values of A and k become 0.6877 and 0.1889°C^{-1} for Q_{10} = 1.4, and 0.6217 and 0.0983°C^{-1} for Q_{10} = 1.8. Fig. 1 illustrates the merging of the two expressions for predicting muscle performance capacity as a function of muscle temperature.

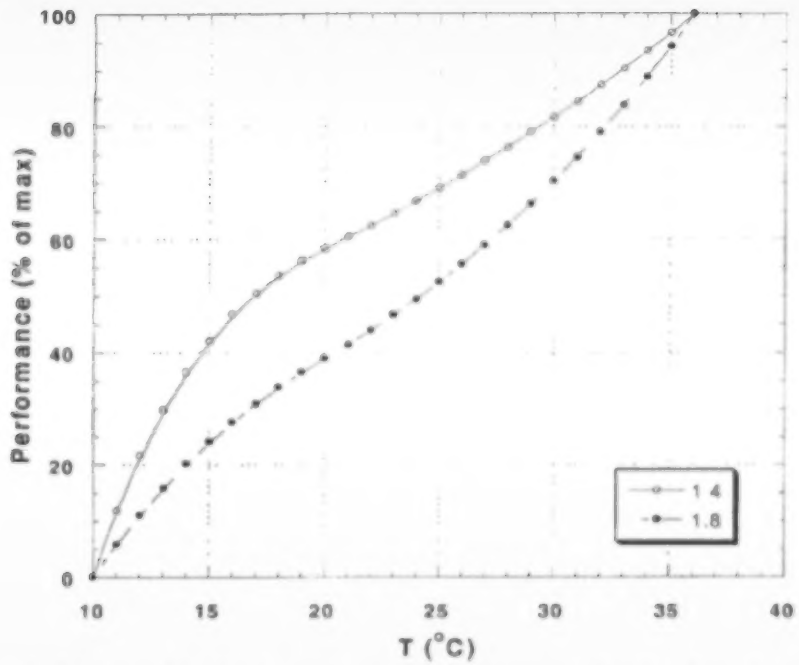

Figure 1. *Prediction of the deterioration in muscle performance as a function of muscle temperature for Q_{10} = 1.4 and 1.8.*

The grip strength of the 50th percentile male between 30 and 39 years of age is 97 kg (Standardized Test of Fitness 1977) and is herein adopted as the reference value. In comparison, the 50th percentile female in the same age group can only exert 54 kg on the grip strength test. Thus, when the average forearm muscle temperature falls to 16.9°C corresponding to a moderate level of deterioration for both genders (see Q_{10} = 1.4 in Fig. 1), grip strength will still be higher for the male (50% of 97 kg = 48.5 kg) vs. the female (50% of 54 kg = 27 kg). Alternatively, the average forearm muscle temperature can be calculated (via Eqs. 1 and 2) to predict at what point the female grip strength is equivalent to 50% of the reference value (i.e., 48.5 kg). Thus, the forearm muscle temperature for a maximum grip strength of 48.5 kg becomes 32.8°C for the 50th percentile female in the age group from 30 to 39 years. Table 3 shows the corresponding predicted average forearm muscle temperatures (based on a Q_{10} value of 1.4) for both genders of various age groups and three levels of individual strength from strong to weak. Note that in the case of weak females (10th percentile), and those at the 50th percentile level and > 59 years old, normal (pre-exposure) grip strength is normally less than 48.5 kg. Therefore, Table 3 has no entry for these cases. CESM provides a secondary output (Table 2) of the prediction of the times to the average forearm muscle temperatures shown in Table 3 and it displays a time of < 0.1 h for those individuals whose normal grip strength is below 48.5 kg. In cases where the muscle

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temperature remains above the reference value even when Tcore reaches 32°C, the predicted endpoint will be based on when Tcore = 32°C, i.e., when all meaningful performance ceases

Table 3. Predicted average forearm muscle temperature (°C) for a maximum grip strength of 48.5 kg. Null entries ("-") indicate that normal grip strength is less than the reference value. The 90th, 50th, and 10th percentiles represent strong, average, and weak individuals, respectively.

GENDER	PERCENTILE	AGE GROUP					
		17 - 19	20 – 29	30 – 39	40 – 49	50 – 59	60 - 65
male	90th	15.2	14.9	14.8	15.0	15.7	16.3
	50th	17.9	17.0	16.9	17.3	18.9	20.4
	10th	25.5	23.0	22.7	23.9	26.4	28.2
female	90th	24.3	26.4	26.0	26.0	28.2	31.7
	50th	33.4	33.4	32.8	33.9	35.1	-
	10th	-	-	-	-	-	-

Comparison of push-ups performance is further complicated by the fact that the amount of effort involved is relative to the body mass that is being lifted. To arrive at a common and meaningful reference point as above, the number of push-ups were multiplied by the mass lifted to yield kg·lifts as a measure of maximum sustained heavy work. According to centre of mass considerations (Resnick and Halliday 1966) for lifting a body using the feet as the pivot point, the force exerted by the arms is approximately 2/3 of the body weight (P. Meunier of DCIEM, private communication). Thus, for males between 30 and 39 years of age, the 50th percentile repetitive (no time limit) push-ups performance is 968 kg·lifts (Standardized Test of Fitness 1977), and one-half of this value will serve as the reference point. In contrast to grip strength, younger males outperform older males and, therefore, the reference value can be exceeded. The push-ups data of females must be adjusted since females were only required to lift part of their bodies using their knees as the pivot point (Standardized Test of Fitness 1977). Consequently, the body mass involved in the data conversion is reduced by 50% (P. Meunier) to reflect the actual force exerted on the arms. A final arbitrary body mass adjustment was also made under the assumption that strong individuals (90th percentile) are less fat than weak individuals (10th percentile).

Table 4 shows the predicted average muscle (forearm and upper arm using a Q_{10} value of 1.8) temperatures for individuals to achieve a maximum sustained heavy work output equivalent to 50% of the maximum output of the 50th percentile male between 30 and 39 years of age at normal body temperature, or the equivalent of 434 kg·lifts in repetitive push-ups.

It turns out that neither males nor females at the 10th percentile performance level are able to achieve the target performance under normal body temperature, and therefore Table 4 excludes these individuals. The normal maximum repetitive push-ups performance of females at the 50th percentile level and > 19 years old is also less than 434 kg·lifts, and therefore,

Table 4 has null entries in these cases. As with grip strength, the revised CESM provides a secondary output (Table 2) that predicts the times to the average muscle temperatures shown in Table 4 and it displays a time of < 0.1 h for individuals whose normal maximum repetitive push-ups performance is less than 434 kg·lifts.

Table 4. *Predicted average forearm and upper arm muscle temperature (°C) for maximum repetitive push-ups equivalent to 434 kg lifts. Null entries ("-") indicate that normal performance is less than the reference value. The 90th and 50th percentiles represent strong and average, individuals, respectively. The 10th percentile (weak) individual is incapable of achieving the reference performance at normal body temperature and, thus are excluded.*

GENDER	PERCENTILE	AGE GROUP					
		17 - 19	*20 – 29*	*30 – 39*	*40 – 49*	*50 – 59*	*60 - 65*
male	*90th*	15.6	16.2	17.4	19 8	21.8	22.5
	50th	20 4	21 9	24.2	26 8	30 5	32 0
female	*90th*	27.7	28.1	28.0	30.5	33.1	35.2
	50th	34.5	-	-	-	-	-

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Revised CESM output

Figure 2 displays the input and output screens of the revised CESM (v. 2.2), in this example for an average 45 yr old male immersed in 10°C calm water wearing regular clothing (shirt, light sweater, and jacket). Previously, only FT (functional time) and ST (survival time) were predicted. Presently, additional predictions of hand and arm functional limits are provided. It is inherently assumed that the hands are bare in all circumstances irrespective of whatever clothing is chosen. In summary, the primary outputs also include the times to moderate and severe losses of hand dexterity and arm performance based on when the individual's tissue temperatures reach specific threshold values (Table 2). In the example shown, moderate losses of hand and arm performance occur at <0.1 and 2.5 h, respectively, and severe losses occur at 4.6 h (by default since the body's core temperature is predicted to reach 32°C at this time). The secondary outputs are referenced to 50% of maximum performance of the average 30 – 39 yr old male. In the example shown, grip strength reaches the reference point at 3.9 and 0.6 h for average and weak 45 yr old males, respectively (forearm muscle temperature for strong individuals exceeds the reference value when T_{core} reaches 32°C, hence no output value is shown since it is deemed irrelevant). Push-ups performance reaches the reference point at 4.3, 0.5, and < 0.1 h for strong, average, and weak 45 yr old males, respectively, in this example. Output times of < 0.1 h indicate that the individual is incapable of performing at the reference level even at normal body temperature.

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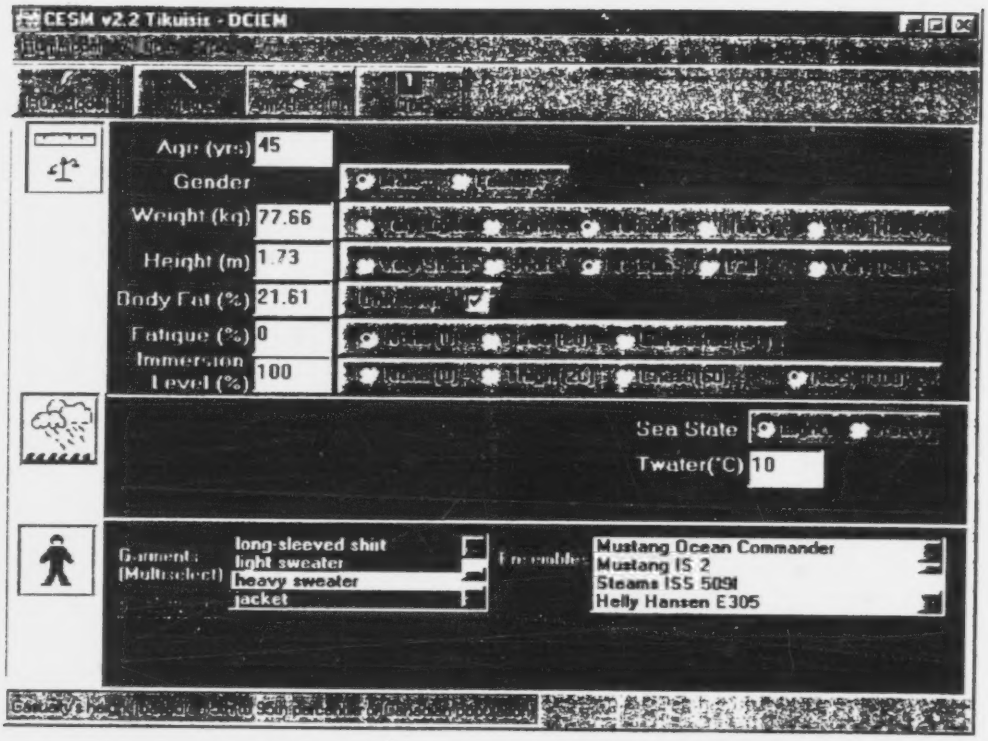

Figure 2a. *Model input screen for immersion of a 45 yr old male in 10°C calm water wearing regular clothing (shirt, light sweater, and jacket).*

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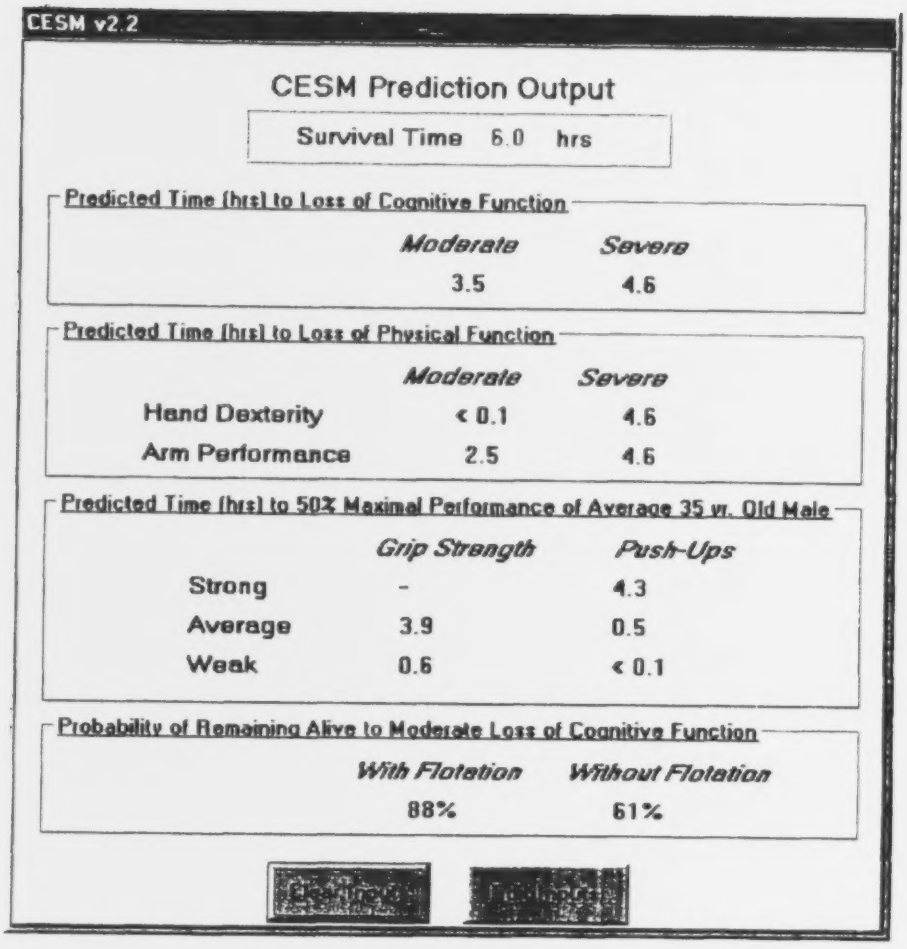

Figure 2b. Model output screen for immersion of a 45 yr old male in 10°C calm water wearing regular clothing (shirt, light sweater, and jacket).

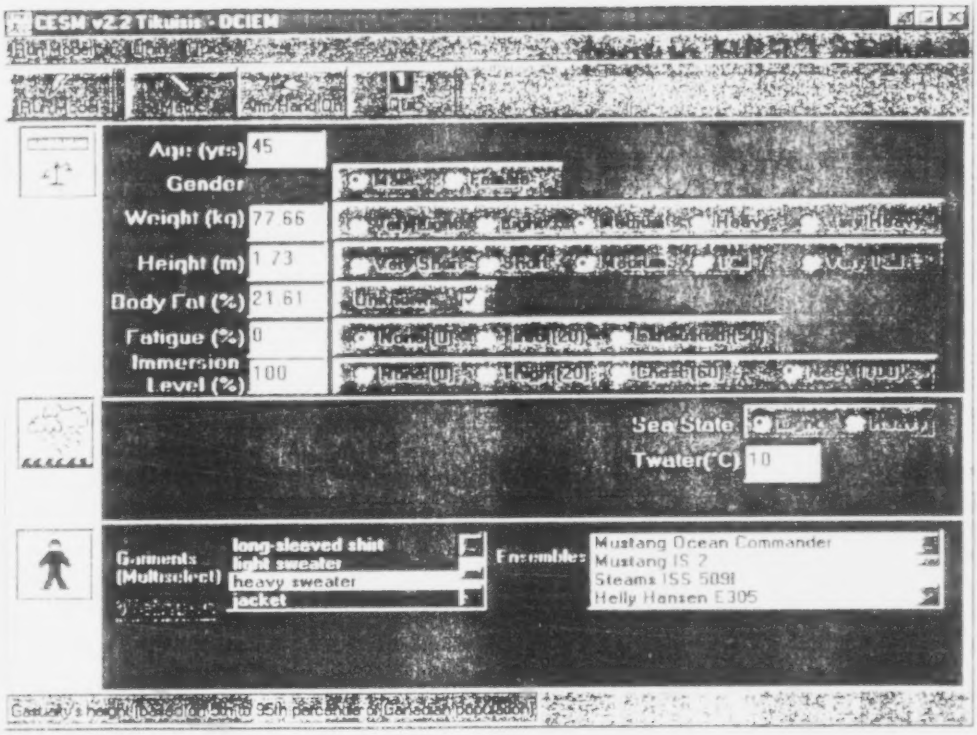

Figure 2a. Model input screen for immersion of a 45 yr old male in 10 °C calm water wearing regular clothing (shirt, light sweater, and jacket).

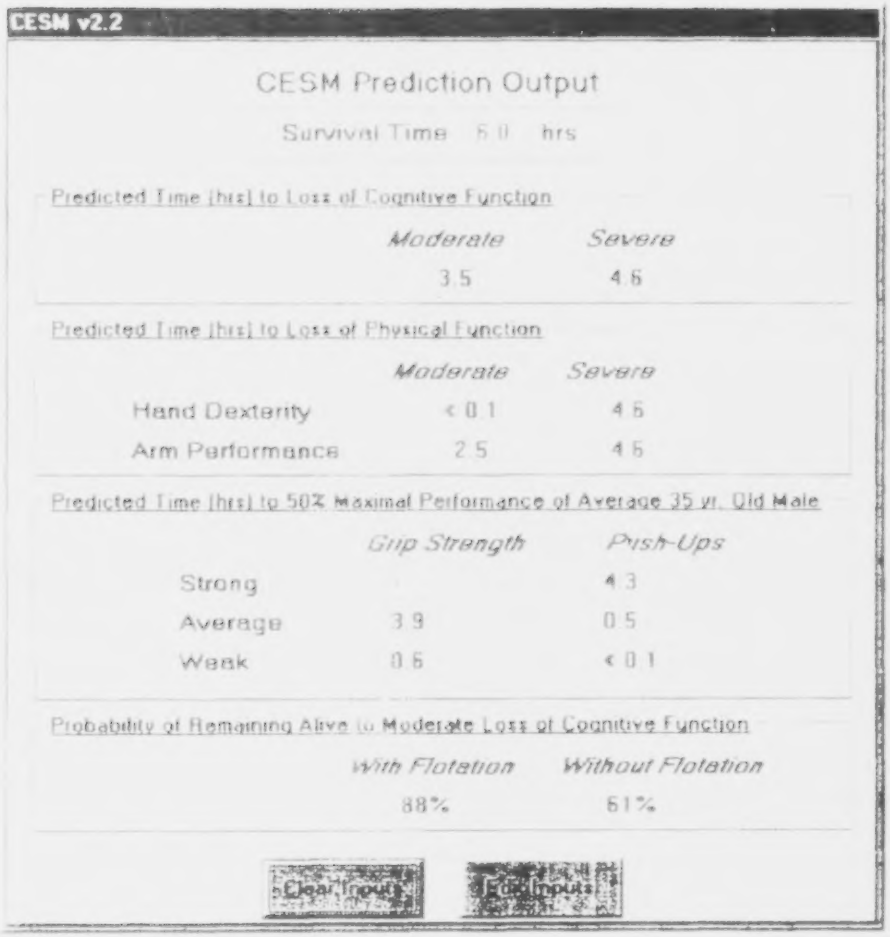

Figure 2b. Model output screen for immersion of a 45 yr old male in 10°C calm water wearing regular clothing (shirt, light sweater, and jacket).

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List of symbols/abbreviations/acronyms/initialisms

CESM	Cold Exposure Survival Model
DND	Department of National Defence
FT	Functional Time
ST	Survival Time
RCS	Rating of Cold Sensation
RPE	Rating of Perceived Exertion
SERE	Survival Evasion Resistance and Escape

Glossary

T	temperature
Q_{10}	factor of change for a 10°C change in tissue temperature

DOCUMENT CONTROL DATA SHEET

1a. PERFORMING AGENCY	2. SECURITY CLASSIFICATION
DCIEM	UNCLASSIFIED Unlimited distribution -
1b. PUBLISHING AGENCY	
DCIEM	

3. TITLE

(U) Arm/Hand Cooling In The Cold Exposure Survival Model

4. AUTHORS

Peter Tikuisis Allan A. Keefe

5. DATE OF PUBLICATION	6. NO. OF PAGES
November 4 , 2001	

7. DESCRIPTIVE NOTES

8. SPONSORING/MONITORING/CONTRACTING/TASKING AGENCY

Sponsoring Agency: DND New Search and Rescue Initiatives Program

Monitoring Agency:

Contracting Agency : Laboratory for Exercise and Environmental Medicine, University of Manitoba

Tasking Agency

9. ORIGINATORS DOCUMENT NO.	10. CONTRACT GRANT AND/OR PROJECT NO.	11. OTHER DOCUMENT NOS.
Technical Report TR 2001-157		

12. DOCUMENT RELEASABILITY

Unlimited distribution

13. DOCUMENT ANNOUNCEMENT

Unlimited announcement

14. ABSTRACT

(U) The previously developed Cold Exposure Survival Model (CESM) is limited to predictions of cognitive impairment and survival time (time to lethal hypothermia) under conditions of cold exposure. The present development addresses motor function impairment of the arms and hands that usually occurs before cognitive impairment and well before the onset of lethal hypothermia. Two data sources were used for this purpose, one based on a field study designed to simulate survival situations and the other based on a review of the literature. The field study involved 28 healthy males on survival training divided into five groups and exposed for 6 continuous days on different occasions during two winter seasons. Despite mean (± SD) air temperatures ranging from –24.4 ± 3.9 to 4.4 ± 2.5°C among the groups, deep body temperature (Tcore) remained normal averaging from 37.1 to 37.5°C. However, finger temperature (Tfinger) was significantly correlated to Tair as follows: Tfinger = 16.7 + 0.28×Tair ($r = 0.53$; $p < 0.0001$). Grip strength, knot-tying, and nut-bolt assembly performance decreased most for the coldest-exposed group, which is consistent with the low Tfinger measured for this group (9.4 ± 3.4°C). Percentages of their maximum performance in these respective tasks were 87.5 ± 9.0, 69.2 ± 12.1, and 83.8 ± 18.1%. The following significant regressions were obtained using all the subjects' data: grip strength (%) = 94.7 + 0.30×Tair ($r = 0.48$; $p < 0.0001$); knot-tying (%) = 93.0 + 0.53×Tair ($r = 0.39$; $p < 0.0001$); and nut bolt (%) = 84.1 + 1.33×Tfinger ($r = 0.33$; $p < 0.0002$). No decrement in cognitive performance as evaluated with tests of logical reasoning, planning, and vigilance was found in any of the groups, and is attributed to the subjects' maintenance of a normal Tcore. These data were consistent with other studies conducted under controlled laboratory conditions and were used in a revision of CESM. The revised model predicts the times to moderate and severe losses of hand and arm function based on local tissue/muscle temperature (15 and 4°C for the finger, and 21 and 10°C for the arm, respectively). Additional predictions are the times to a reference performance level based on 50% of the maximal effort of an average mid-age male under normal body temperature. In this case, the predicted performances are instantaneous maximal force (as determined by grip strength) and sustained high intensity work effort (as determined by repetitive push-ups). These additional predictions should provide a more complete assessment of a casualty's survival status in the revised CESM.

15. KEYWORDS, DESCRIPTORS or IDENTIFIERS

(U) body cooling, modelling, prediction, survival time

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